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Low Cycle Fatigue Crack Propagation Characteristics of Monel 400 and Monel K-500 Alloys

T. W. Crooker, R. E. Morey, and E. A. Lange

Strength of Metals Branch
Metallurgy Division

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U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

Tests were conducted on Monel 400 and Monel K-500 plate bend fatigue specimens. Rapid crack initiation was achieved by means of a mechanical surface notch, and crack growth rates were monitored under constant-total-strain-range full-reverse cycling. Test conditions included a variety of strain range values in both air and simulated salt water environments.

It was found that low cycle fatigue crack growth rates can be expressed as an exponential function of applied total strain range. Based on this function a method was devised for comparing the low cycle fatigue crack propagation characteristics of a variety of materials. This method takes into account yield strength level, elastic modulus, and the effects of a corrosive environment.

PROBLEM STATUS

This report completes one phase of the problem. Work on other aspects of the problem is continuing.

AUTHORIZATION

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LOW CYCLE FATIGUE CRACK PROPAGATION CHARACTERISTICS OF MONEL 400 AND MONEL K-500 ALLOYS

INTRODUCTION

The safe and dependable application of modern high strength materials to large cyclically loaded structures, such as pressure vessels and submersible vehicles, requires an improved knowledge of slow crack propagation resulting from low cycle fatigue. Small flaws and cracks invariably are formed during fabrication and manufacture of a large welded structure despite the use of the best available processing and inspection techniques. Since fabrication flaws are unavoidable, the only practical recourse is to provide design criteria for preventing the growth of such probable cracks to a critical size from repeated service loads.

The overall aim of this investigation is to define and evaluate the factors which control the growth of cracks under low cycle fatigue conditions and ultimately to develop a method for predicting the life for high performance structures. The results of the current phase of this investigation are based on studies of crack propagation in center-notched plate bend specimens loaded in cantilever fashion. Preliminary evaluations of the low cycle fatigue characteristics of a variety of quenched and tempered steels and 2024 aluminum alloy have been made (1-4). Briefly, it has been observed that for a specific environment and strain ratio the growth rate of a low cycle fatigue crack is dependent upon applied total strain range, as expressed by the relationship

$$\Delta L/\Delta N = K(\epsilon_T)^n \qquad (1)$$

where L is the total length of the fatigue crack, N is the cycle of loading, K is a constant, ϵ_T is the total (elastic plus plastic) strain range, and n is a constant.

This relationship remains valid in the presence of mean strains other than zero and in the presence of aqueous corrosive environments. However, it has been observed that both of these factors affect crack growth rate. Mean strain can either accelerate or retard crack growth rate, depending upon whether it is tensile or compressive. Corrosive environments tend to accelerate crack growth rate, depending upon such factors as corrosion resistance, stress corrosion, and hydrogen embrittlement.

This report discusses the low cycle fatigue crack propagation characteristics of two Ni-Cu (Monel) alloys of widely different strength levels tested in room-temperature air and simulated salt water environments. They are presented for discussion because of their own importance as specialized structural alloys and, further, because the analysis discussed here is pertinent to other materials, such as steel and titanium, where comparisons between fatigue crack propagation in low strength versus high strength alloys must be made for design considerations.

MATERIALS AND SPECIMENS

The materials employed in this experiment consisted of Monel 400 and Monel K-500 alloys. Chemical compositions and mechanical properties of these alloys are given in Tables 1 and 2, respectively. The Monel 400 was tested in the as-received condition.

Table 1
Chemical Composition of Two Monel Alloys

Material	Composition (wt-%)								
	C	Mn	Fe	S	Cu	Si	Ni	Ti	Al
Monel 400	0.17	0.97	1.64	0.008	32.24	0.11	64.84	-	0.009
Monel K-500	0.16	0.57	1.57	0.005	30.21	0.14	63.91	0.52	2.89

Table 2
Mechanical Properties of Two Monel Alloys

Material	BHN	0.357-in.-diam Tensile Test Data			
		YS (0.2%) (ksi)	UTS (ksi)	Elongation (1/4-in. gage length)	RA (%)
Monel 400	149	35	86	46	39
Monel K-500	179	103	154	25	31

Monel K-500 specimens were given an age-hardening heat treatment consisting of heating to 1100°F for 16 hours followed by furnace cooling before being tested. Photomicrographs of these two alloys are shown in Fig. 1.

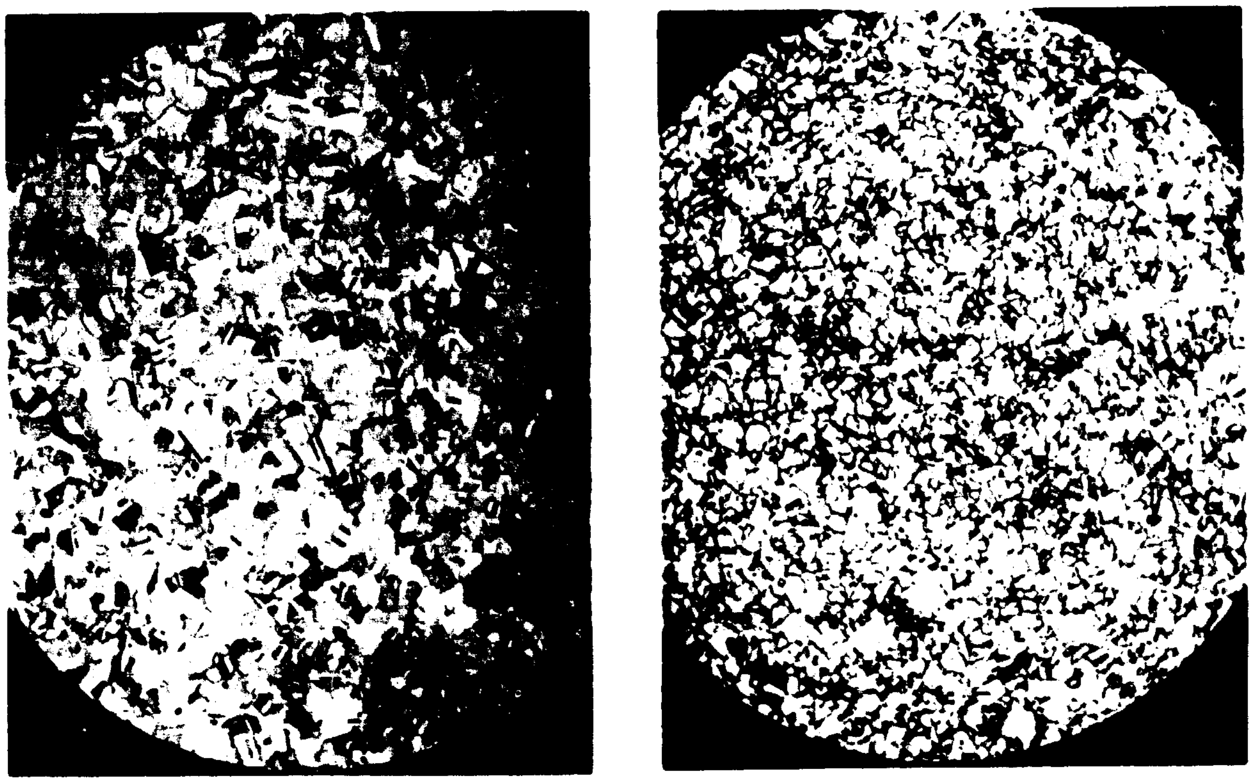
Fatigue tests were conducted using center-notched plate bend specimens of the type developed by Lehigh University, shown in Fig. 2 and described in Ref. 5. This specimen possesses several advantages for crack propagation studies. Its width at the test section is five times its thickness, which results in considerable lateral restraint in bending. Because of this restraint an effective lateral strain equal to approximately one half the longitudinal bending strain exists across the test section. Such a biaxial strain ratio simulates many actual applications of structural materials.

In addition, the test section of the plate bend specimen is easily accessible for strain measurements and crack growth observations. The fatigue crack initiates at the center notch and propagates through the test section perpendicular to the longitudinal (principal) tensile strain. Crack growth rate data are based on measurements of the visible portion of the fatigue crack along the surface of the test section.

Fatigue specimens were machines from rolled plate stock. Specimen orientations were chosen so that the fatigue crack propagation was parallel (WT) and perpendicular (RT) to the rolling direction, respectively.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental setup employed in this series of tests consisted of six automatic plate bend fatigue machines designed by the U.S. Naval Marine Engineering Laboratory



(a) Monel 400 (b) Monel K-500

Fig. 1 - Photomicrographs of Monel 400 and Monel K-500 alloys (100X)
Reduced approximately 36% in printing

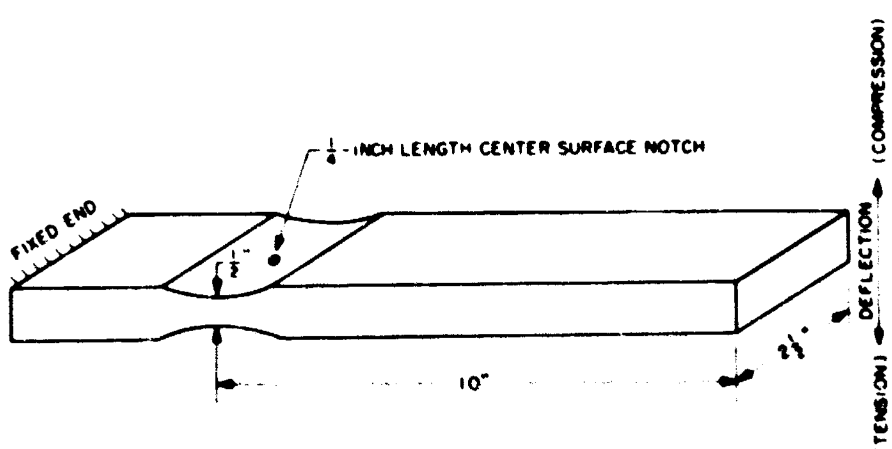


Fig. 2 - Lehigh-type plate bend fatigue specimen

and adapted for crack propagation studies by NRL (Fig. 3). The machines are provided with dial indicators and microswitch adjustments for deflection control. A load cell is placed in series with the actuating hydraulic cylinder to obtain load measurements. Nominal bending strains across the test section are measured with resistance-type strain gages. Signals from these two devices are combined on an X-Y recorder to generate load-strain hysteresis loops, shown schematically in Fig. 4. Crack length observations are made by means of an optical micrometer.

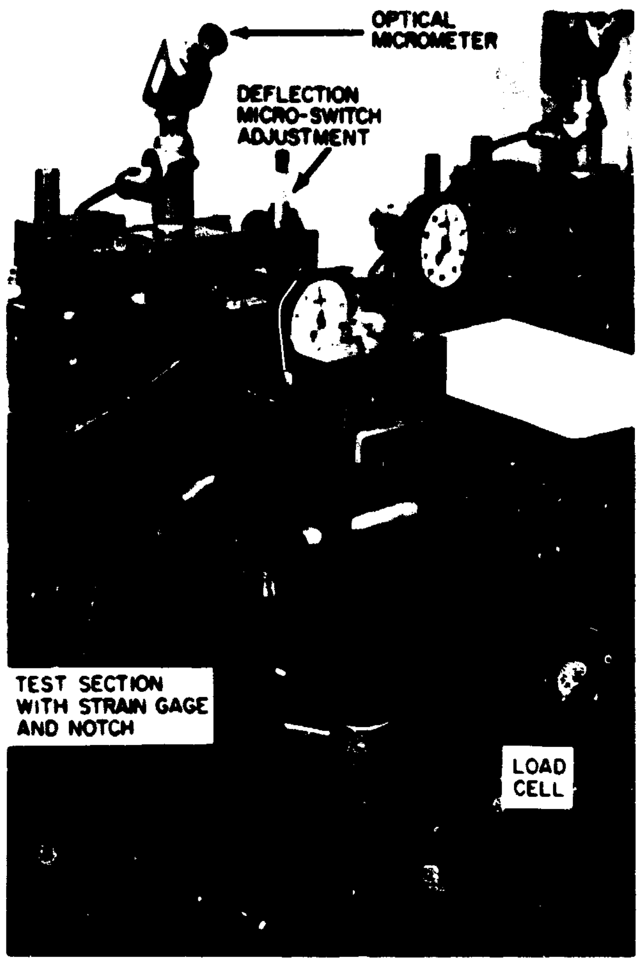


Fig. 3 - NRL low cycle plate bend fatigue machine

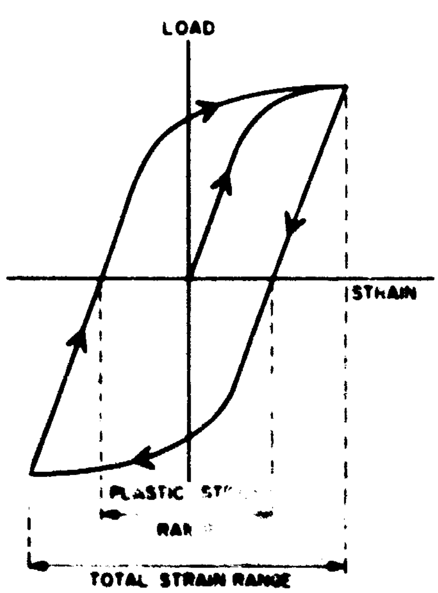


Fig. 4 - Schematic diagram of full-reverse bending fatigue loading cycle

The first step in the experimental procedure was to obtain the strain-range-vs-deflection characteristics of each material with an unnotched specimen (Fig. 5). These measurements are useful for obtaining the proportional limits of the respective materials, which is arbitrarily defined as 500 micro-in./in. plastic strain range in a full-reverse bending cycle. This value is chosen as the smallest plastic strain range which can be detected with accuracy. In addition, these measurements are helpful in estimating the value of applied total strain range which will assure rapid crack initiation from the mechanical notch and the limiting total strain range values which will be pertinent to crack propagation studies.

Once this step has been taken, notched specimens were then tested in fatigue. During crack propagation tests, total strain range measurements are monitored and held constant over specific intervals ranging from several hundred to several thousand cycles by adjusting deflection. Crack growth is also closely monitored during these intervals to obtain data for crack growth

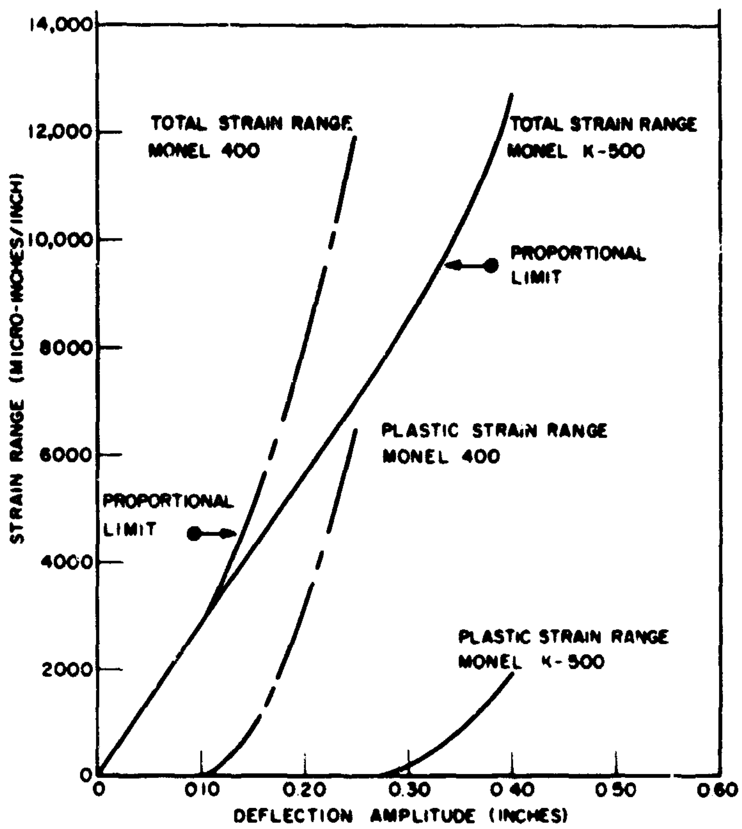


Fig. 5 - Strain range-deflection characteristics of Monel 400 and Monel K-500 plate bend fatigue specimens in full-reverse loading cycle. For each specimen the proportional limit point is determined by the smallest value of plastic strain range (500 micro-in./in.) which can be detected with accuracy.

rate calculations. Each specimen is tested at a series of constant total strain range values, and the resulting data are plotted on a log-log curve of crack growth rate versus total strain range (see Eq. (1)). In this manner the crack propagation characteristics of the two materials were examined.

For tests which included the effect of a simulated salt water environment, a portion of the test specimen including the fatigue crack is covered by a corrosion cell. The cells are made of molded polyurethane which is soft and flexes with the specimen. A 3.5% salt water solution was circulated through the corrosion cell from a reservoir.

RESULTS AND DISCUSSION

Strain Range Effects

Figure 6 is a log-log plot of laboratory data showing crack growth rate as a function of applied total strain range (elastic plus plastic strain) for the two Monel alloys in an air environment. These data follow the exponential relationship of Eq. (1) between crack growth rate and total strain range.

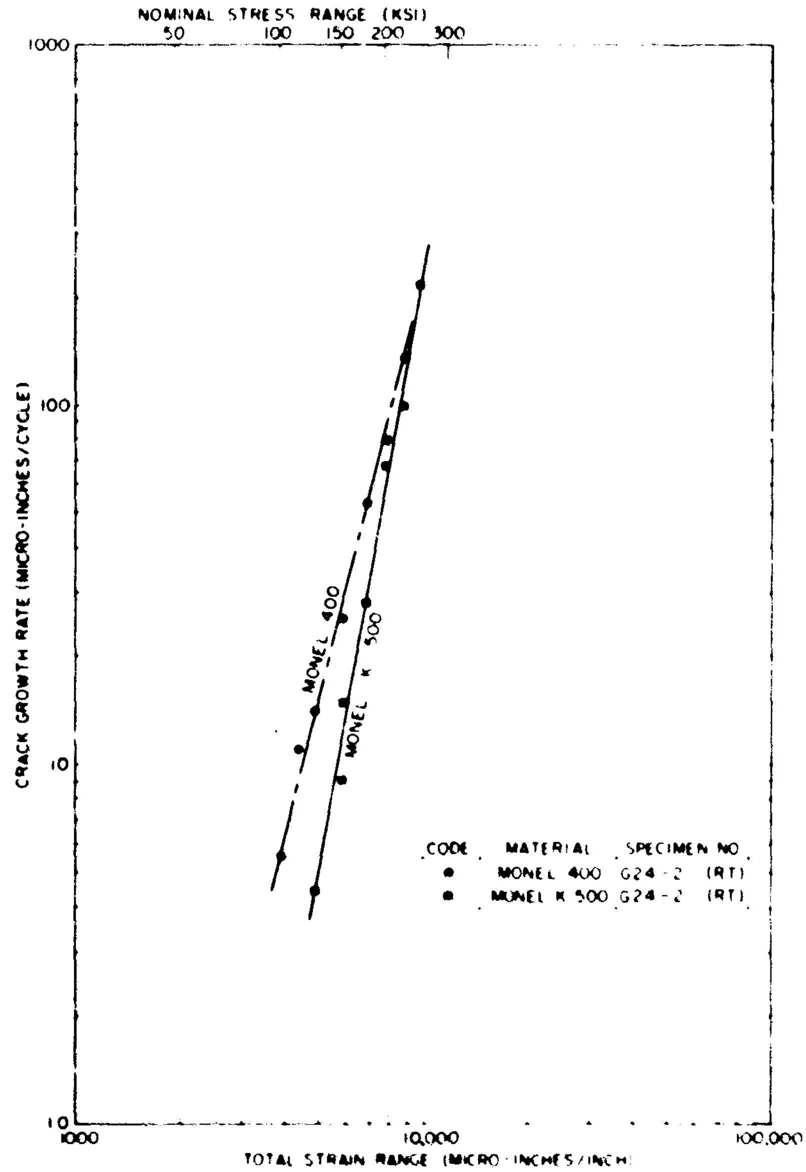


Fig. 6 - Log-log relationship between applied total strain range and crack propagation rate data in full-reverse bending for Monel 400 and Monel K-500 alloys in an air environment

The usefulness of this relationship for presenting laboratory data is apparent; however, as a means of comparing the low cycle fatigue performance of competing materials for design applications, it can be misleading. On the basis of the curves shown in Fig. 6, it would appear that the higher strength Monel K-500 is superior to the lower strength Monel 400, at least throughout a large portion of the strain range values tested. This comparison would in itself be valid if the application of these materials were solely confined to elastic strain conditions. However, low cycle fatigue crack propagation is a plastic flow process associated with small flaws and cracks in large structures under nominal elastic loading. Therefore, crack propagation comparisons based on total strain range values must consider the yield strength level and, when making broader comparisons, account for variations in the moduli of elasticity.

A more practical comparative criterion is obtained by converting strain units to the ratio of the total strain range to the proportional limit strain range, which results in

the emergence of an entirely different comparative relationship between the two materials (Fig. 7). Here it becomes apparent that the higher strength Monel K-500 possesses very little tolerance for plastic strains and, in fact, develops a rapid crack growth rate while in the elastic region. Similar relationships for HY-80 steel and 2024 aluminum are also shown in Fig. 7 for comparison (4). Any design based on a fixed percentage of the yield strength as its criterion must take this characteristic into consideration when evaluating the possible application of higher strength materials. Consideration must also be given to the detrimental effects of substituting materials with lower elastic moduli.

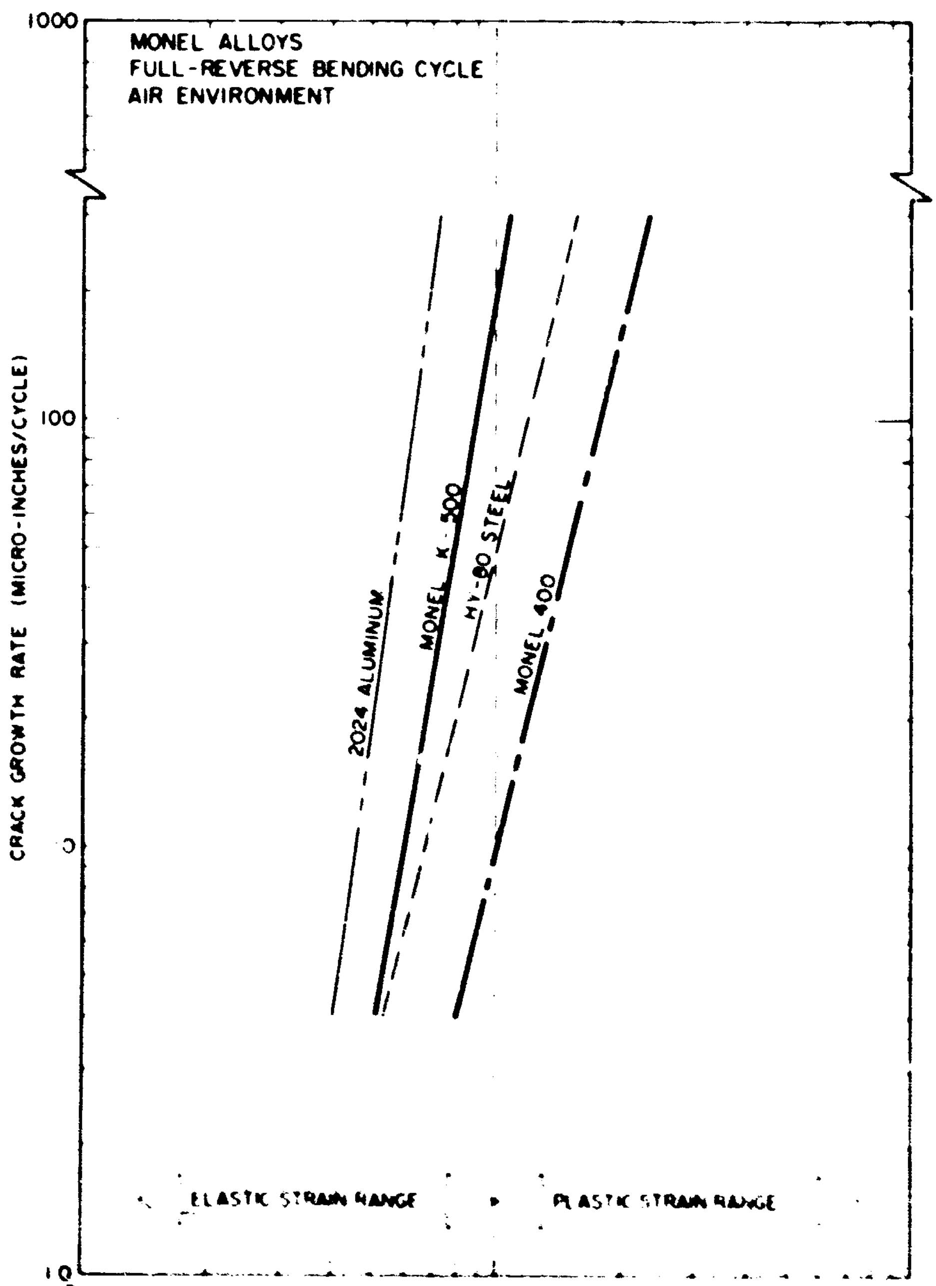


Fig. 7 - Relationship between the ratio of total strain range to proportional limit strain range and the crack propagation rate for two Monel alloys in full-reverse bending in an air environment. The proportional limit strain range is defined as 500 micro-in./in. plastic strain range in plate bend fatigue specimens. The 2024 aluminum and HY-80 steel relationships are shown for comparison.

A further insight into the difference in low cycle fatigue behavior of these two alloys can be seen by a visual examination of the fatigue cracks formed during full-reverse bend cycling (Fig. 8). Both photographs are taken at the same magnification (14X) and differ only in the total length of the fatigue crack. The fatigue crack through the relatively ductile, low strength Monel 400 shows signs of extensive plastic deformation and cold working in the vicinity of the crack. In contrast, the higher strength, age-hardened Monel K-500 formed a small jagged crack with very limited plastic deformation in a region near the crack tip. These photographs illustrate the comparative ease with which fatigue cracks can penetrate high strength materials at elastic stress levels near the proportional limit.

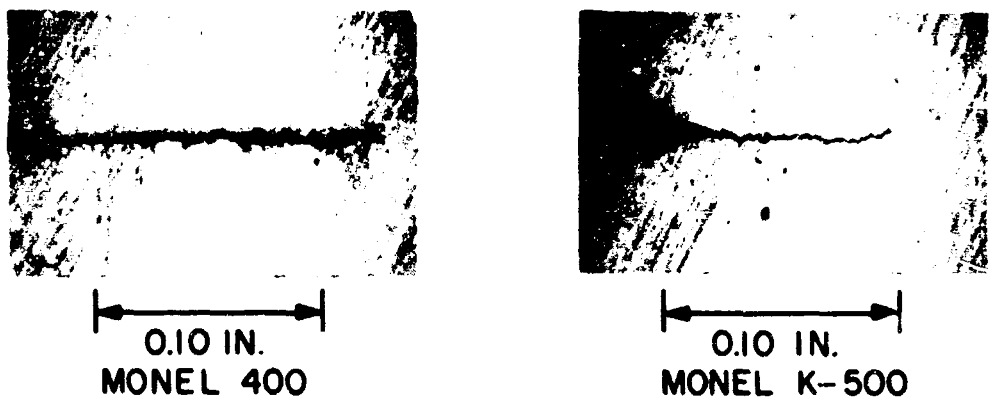


Fig. 8 - Fatigue cracks formed in Monel alloys during full-reverse bending (14X)

Corrosion Fatigue Effects

Since Monel alloys are special purpose materials employed mainly because of their superior corrosion resistance, the two materials considered in this report were also tested under a corrosive environment. A 3.5% simulated salt water solution was chosen because of its availability, reproducibility, and importance to naval applications. The crack propagation data from these tests are shown in Figs. 9 and 10.

In judging corrosion fatigue performance, a basis for rating a given material can be obtained by comparing the log-log plot of crack propagation rate versus applied total strain range data in the corrosive environment with similar data taken in an air environment. For this reason, the respective plots of data obtained in air are superimposed on the data shown in Figs. 9 and 10. This comparison provides an estimate of the degree to which corrosion conditions accelerate low cycle fatigue crack propagation in the presence of a given applied cyclic strain.

On this basis of comparison, the fatigue performance of Monel K-500 was essentially unaffected by the presence of salt water (Fig. 9). Only a small increase in crack growth rate can be noted at higher strain values when compared with growth rates in air. This small increase in growth rate is attributed to the onset of generalized plastic strain conditions at strain range values near the proportional limit. Previous tests have shown that crack propagation resistance can be reduced by corrosive mechanisms much more rapidly under plastic strain conditions (3).

In contrast, Monel 400 showed an increase in the scatter and a slightly inferior fatigue resistance throughout the range of strain values tested in salt water (Fig. 10). Crack propagation rates were approximately doubled by the addition of salt water. However, it

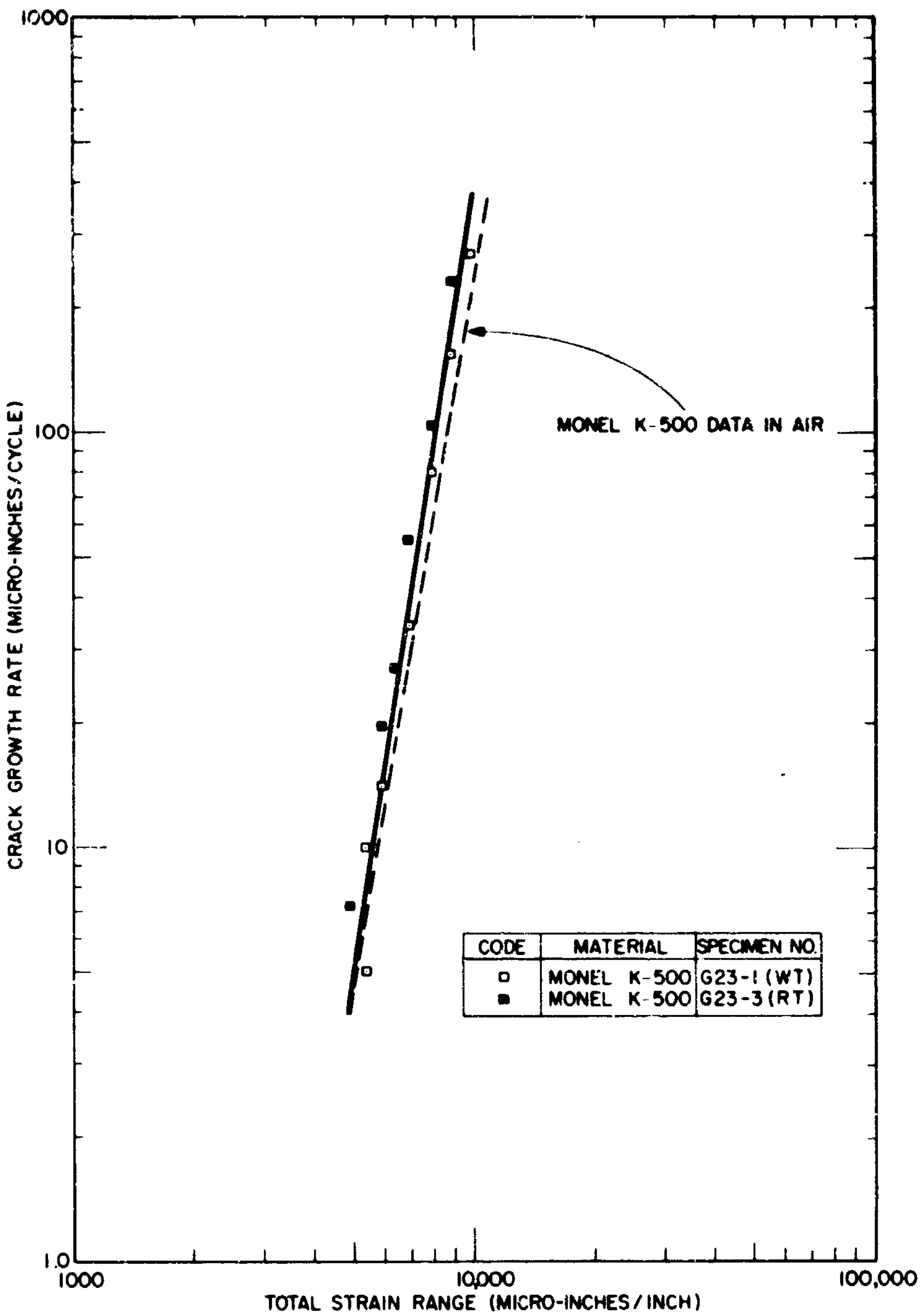


Fig. 9 - Log-log relationship between applied total strain range and crack propagation rate data in full-reverse bending for Monel K-500 alloy in a simulated salt water environment

must be noted that Monel 400 was tested under conditions of considerably more applied plastic strain than Monel K-500 in order to attain crack growth rates pertinent to low cycle fatigue.

The greater sensitivity of Monel 400 to environment under plastic strain conditions is predictable. Both alloys displayed good resistance to low cycle fatigue crack propagation in the presence of simulated salt water when compared to quenched and tempered steel, especially under elastic loading where applied strains are kept below the proportional limit.

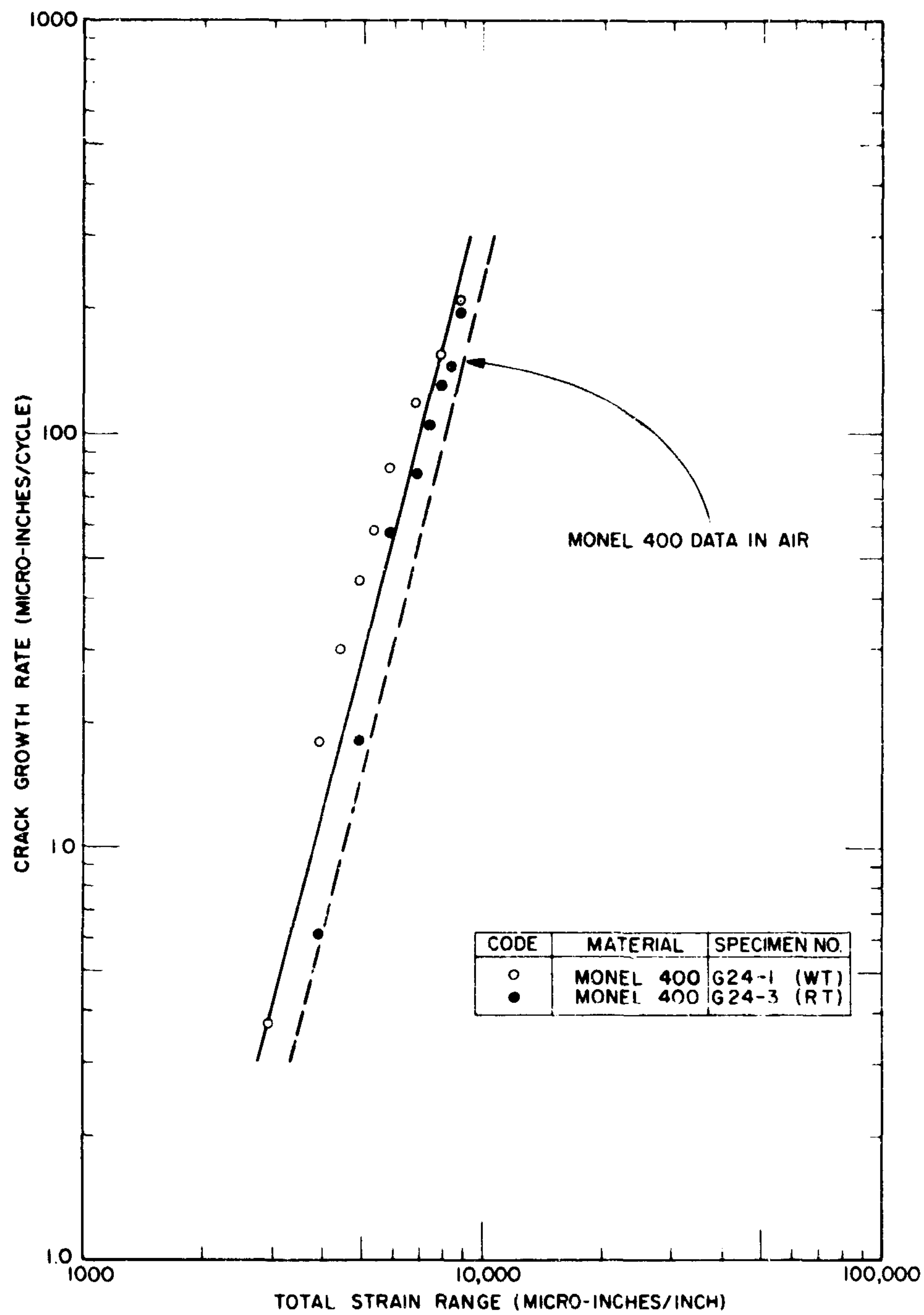


Fig. 10 - Log-log relationship between applied total strain range and crack propagation rate data in full-reverse bending for Monel 400 alloy in a simulated salt water environment

The data from Monel 400 in salt water (Fig. 10) appear to indicate growth rate is affected by orientation with respect to rolling direction. This trend was not as evident in the Monel K-500 data (Fig. 9) or in any previous data (1-4). All evidence to date indicates that low cycle fatigue crack growth rate is not sensitive to rolling direction orientation. The significance of the trend for an effect from orientation for these specimens requires additional study with material rolled under a variety of conditions.

CONCLUSIONS

1. Low cycle fatigue crack growth rates in Monel 400 and Monel K-500 alloys follow the strain dependent exponential relationship $\Delta L/\Delta N = K(\epsilon_T)^n$ which has been previously observed for a variety of structural materials.

2. Monel 400 alloy is more resistant to low cycle fatigue crack propagation than Monel K-500 when compared on a basis (such as at a fixed percentage of the yield strength) which takes into consideration the wide difference in strength level between the two materials.

3. In the presence of a salt water environment, the lower strength Monel 400 alloy was subjected to greater plastic strains in the fatigue tests and exhibited a greater reduction in fatigue crack propagation resistance than Monel K-500 alloy. However, both materials showed relatively small decreases in fatigue performance under salt water corrosion conditions.

ACKNOWLEDGMENT

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